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THE ROLE OF CLOTHING IN ACHIEVING ACCEPTABILITY OF ENVIRONMENTA--ETC(U)
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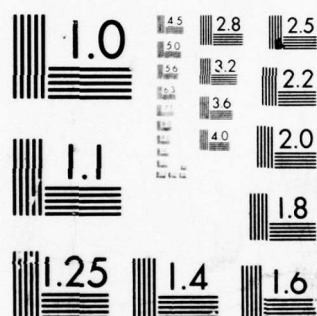
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6 The Role of Clothing in Achieving Acceptability of Environmental
Temperatures Between 65°F and 85°F (18°C and 30°C)

by

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JOB

It is a pleasure to present at this Symposium honoring A. Pharo Gagge but it is also a problem, given my assigned topic "The Role of Clothing in Achieving Acceptability of Environmental Temperatures between 65°F and 85°F (18° to 30°C)." It recalls my student days at Boston Latin School and how I would have felt translating Caesar's "Omnis Gallia in tres partes divisa est" if Caesar were in the classroom; Pharo's contributions to the study of comfort and clothing make it inevitable that anyone working in these areas must draw heavily on them. Indeed, since his contributions to comfort research span more than 40 years beginning, I believe, with a 1935 contribution (#5 from the Pierce Laboratory) on the subject "The Calibration of the Thermo Integrator", it is difficult to delineate where Pharo's ideas are distinct from those who followed his lead. My own research has primarily been at the extreme's of cold, where the best available clothing is unable to protect an inactive individual (and particularly his fingers and toes) against excessive cooling, or at the extremes of heat stress induced by such "clothing" as body armor or chemical protective systems. However, translation of my work on clothing to the more limited range 18-30°C range being addressed in this Symposium is certainly not as much of a departure as Pharo's extension of his Doctoral thesis, on atmospheric ions, to address questions of comfort and "Microgenic Radiation" from household radiators; at least, I have Pharo's contributions over the last 42 years to draw upon.

Reports on thermal comfort are rare before the 1910 ASHVE report by Lyle on "Relative Humidity and Its Effect on Comfort and Health", but the thermal environmental specification for comfort is little changed from the 1914 specifications of 75°F and 35% RH for sedentary conditions (and 68°F and 50% RH for moderate work loads) suggested in the 1923 Report of the New York State Com-

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mission on Ventilation (22), to the current ASHRAE Standard 55-74 recommended comfort zone - a rectangular area on the psychrometric chart, bounded by a 14 mmHg vapor pressure between 71.5° and 77.6°F (21.9° - 25.3°C) at the top (~60% RH) and 5 mmHg between 72.6° and 79.7°F (22.6° - 26.5°C) at the bottom (~20% RH), provided that "air velocity is 70 ft/min (35 cm/sec) or less and the temperatures specified are the "Adjusted Dry Bulb Temperature" (ADBT) derived as one half the sum of air temperature plus mean radiant temperature (2)."

Such a complicated specification of a thermal environment could have been simplified by using the 1923 development by Houghten and Yaglou (19) of the original "Effective Temperature" (ET) Scale. This scale incorporates the air temperature (T_{db}), measured with a dry bulb thermometer, the radiant temperature $[MRT = (1 + .222\sqrt{V})(T_g - T_{db}) + T_{db}]$ if ET corrected for radiation as integrated by a 6" Vernon block thermometer globe (T_g) is desired, the humidity measured by a wet bulb thermometer (and expressed as T_{wb}) and air motion (V), into the single index "ET". This index expresses an equivalence (as originally sensed by a few subjects) between the thermal sensation induced by the effects of a given combination of T_{db} , T_{wb} , V (and MRT if correction for radiation was included) and those induced by the ET temperature at 100% RH with low air motion. Although ET was not a rational index, but rather a subjectively derived one (which overemphasizes humidity effects in cool and comfortable conditions and underemphasizes both humidity in warm conditions and the importance of air motion as humidity rises in the heat), it has served as the standard reference temperature for comfort and performance studies until recently, despite our general unfamiliarity with the sensations of any temperature at 100% RH except perhaps a Turkish bath steam room. Pharo's 1971 introduction of ET^* (12) a rational index based on a simple

model of human physiological regulatory response, references the revised index (ET^*) to a more subjectively familiar 50% RH base, and ET^* is replacing the older index in current comfort literature. The usual range of purely physiological thermoregulation is from 75° to 80°F (24°-32°C) for a 100% RH reference (as in the earlier ASHRAE ET scale), whereas with a 50% RH reference (ET^*) the zone of physiological regulation ranges from 77 to 106°F (25°-41°C). Outside the limits of physiological regulation, ET^* closely follows T_{db} in the cold ($ET^* \approx 1^\circ F < T_{db}$), while in intolerably hot conditions $ET^* \approx 16^\circ F > T_{db}$.

Given the simplicity of ET for specifying the interactions of the four environmental factors of concern in comfort research (air temperature, radiant temperature, humidity and air motion), research was directed toward such factors as geographic and seasonal variation, and the activity level, sex and age of the exposed individuals in the specification of a comfortable condition. As early as 1902, Rubner (24) had postulated that "we cannot neglect those conditions of voluntary regulation which are required by the state of thermal comfort." He revealed a very sophisticated understanding of many factors: the interaction between activity, clothing and comfort; the dependence of clothing insulation on its thickness; the effects of humidity build up in clothing; and the effects of wind on clothing insulation. He reported that, at absolute muscular rest, comfort could be found at three states: undressed at 33°C; wearing summer clothing at 25°C; and wearing fur clothing at 12°C. By 1925, Yaglou and Miller (38) had even suggested how differences in clothing might be incorporated into the ET index for comfort specification. However, despite the critical contribution that even small differences in clothing could make to thermal comfort, clothing was generally ignored as a specific variable until publication of contribution #22 from the J. B.

Pierce Laboratory, Pharo's 1938 study (13). This omission was recognized in the sequence of seminal studies at the Pierce Laboratory involving Partitional Calorimetry (29), Pharo's application to it of the Linearity Criterion (6) from his training in Physics, its use in separating radiation from convective exchanges (30) and their relative influence on vasomotor temperature regulation (15), the physiological reactions to varying environmental temperatures (31) and to various atmospheric humidities (32), Pharo's key paper on "A New Physiological Variable Associated with Sensible and Insensible Perspiration" (7), his "Thermal Interchange Between the Human Body and Its Atmospheric Environment" (9) and the Pierce group's studies on the relationships between the environment, physiological reactions and sensations of pleasantness (33,37). Most of the concepts relating comfort to psychological sensation, skin temperature and the percent sweat wetted area of the body arise from these three years of studies at the Pierce Foundation. The contribution made by Pharo's effective use of his Physics background in these key studies is easily seen.

Unfortunately, many other researchers were either less cognizant that they were omitting effects of clothing differences as a variable in their studies of comfort, or neglected to specify (or even to characterize) the clothing worn in their studies. Thus, Yaglou and Miller (38) indicated that during the winter a 66°ET produced comfort for most people, while 63° to 71°ET would satisfy at least 50% of their subjects. Later studies by Houghten, involving radiation (17) in 1941 suggested 69°ET as the optimum. The 1950 Heating, Ventilating and Air Conditioning Guide (14) indicated that the 68°ET level would be comfortable for almost 98% of the population; the 1950 Guide also suggested that 71°ET , over the range of 30 to 70% RH, would satisfy 98% of the population in the summer, and

that at least 50% of the population would be comfortable over the ET range 66.5 to 75°F.

These summer winter differences were extended to include differences within the U. S. as a function of latitude (4) with 73°ET preferred south of the 35th parallel, 72°ET between the 35th and 40th, 71°ET from the 40th to 45th and 70°ET above 45° of latitude. Canadian studies (23) supported the summer winter difference, with a 66.5°ET optimum in winter and a 70.5°ET optimum in summer. Studies of people (primarily women) working in light industry in Britain (3) suggested 60.8°ET as an optimum, with 60-68°ET judged comfortable by 70% or more. These British values were confirmed in a 1955 study of over 2,000 subjects in Britain (16) with 60.8°ET (61.7° CET) reported as optimum and 66°ET (68° CET) as an upper limit in winter and 62.9°ET (64.4° CET) as optimum in summer, with 70°ET (71° CET) as an upper limit. Houghten, in 1941, (18) also suggested that the optimum condition for women was 1°ET higher than for men, and that men and women over 40 years of age preferred a 1° greater ET than younger men and women.

We now recognize that, while some of these reported differences were associated with small differences in metabolic heat production, with an increase in heat production of 29 watts (25 kcal/hr) enough to offset a 1.7°C (3°F) reduction in the T_{db} for comfort (1), the majority of these reported differences reflected the failure to standardize clothing. Today, no differentiation of the comfort zone is recommended as a function of sex, season or geographic location (1,5).

One possible explanation for the failure to specify clothing in these early studies was that there was no basis for comparing the insulation provided by various clothing systems. It was obvious, from the physics of heat transfer, that the con-

vective heat exchange (H_c) between the skin surface and the ambient air could be described by a function of the form:

$$H_c = k A (T_s - T_{db})$$

where A was the skin surface area, T_s was the average skin surface temperature, T_{db} the air temperature and k was the convective heat transfer coefficient. Pharo's application of the first law of thermodynamics, and its linearity criterion (6) helped suggest the form of the heat balance equation:

$$M + A_r R - C (T_s - T_A, V) - E + S = 0$$

where M was the metabolic heat production, $A_r R$ represented the radiative heat exchange function, $C(T_s - T_A, V)$ represented the convective heat exchange function, E represented evaporative heat losses and S represented body heat storage.

He and Drs. Winslow and Herrington then explored this convective heat exchange function for two nude subjects (30) and showed that it could be expressed as:

$$C = k\sqrt{V} (T_s - T_{db})$$

where V was expressed in feet per minute and the temperatures were in $^{\circ}\text{C}$. They reported k as $2.30 \text{ kcal/hr } ^{\circ}\text{C}$ for the subject with 2.13 m^2 of surface area, and as 1.87 for the subject with 1.49 m^2 . The group went on to introduce a new "operative temperature" (T_o), representing the net effect of both air and wall temperatures; i.e. convective and radiative heat exchanges (31) and in 1938 presented work on Clothing and Bodily Reactions to Temperature (13) by Gagge, Winslow and Herrington, whereby "it is possible at any time to estimate the radiation exchange, R , and convection loss, C , by use of the following relations:

$$R = k_r (T_{cl} - T_w),$$

and

$$C = k_c (T_{cl} - T_A)$$

where T_{cl} is the mean surface temperature of body and clothing exposed to the environment. Adding . . . ,

$$R + C = k_o (T_{cl} - T_o)$$

where k_o equals the sum of k_r and k_c , and the operative temperature, T_o ,"

The next 1938 study, on "The Relative Influence of Radiation and Convection upon the Temperature Regulation of the Clothed Body" Pierce Contribution #23 (34) led to a prediction equation for skin temperature ("valid where evaporation is minimal") and relationships between the skin temperature and subjective reports of pleasant, indifferent and unpleasant. The Pierce final study for 1938 in this area Contribution #24 (35) explored humidity effects for clothed subjects and the significance of the wetted area, while Contribution #25 (36) explored "The Influence of Air Movement upon Heat Losses from the Clothed Human Body."

The stage was now set to define a clothing insulation unit and, in 1941 (8), Pharo, in collaboration with Burton and Bazett, defined the clo unit, referenced to a typical business suit of that era, from the physical relationship:

$$\text{Resistance} = \text{Potential Difference} / \text{Flow}$$

The potential difference for non-evaporative heat loss (i.e. $H_{R\&C}$ from the human skin) is, obviously, the difference between skin temperature (T_s) and ambient temperature (T_{db} or, if $T_{db} \neq MRT$, T_o). The available heat flow was taken as the total resting heat production ($M=1 \text{ MET} = 50 \text{ kcal/m}^2 \text{ hr}$) minus the 24% of M lost

by both evaporation of the moisture diffusing from the skin and respiratory heat exchange. Thus:

$$R = (T_s - T_o)/(0.76 \times 50)$$

With a "comfortable" skin temperature of 33°C and a typical office temperature (for 1941), of 21°C (70°F), the resistance to convective and radiative heat loss (R) for a man dressed for the office was:

$$R = (33-21)/38 = 0.32^{\circ}\text{C/kcal m}^2 \text{ hr}$$

Previous work at the Pierce Laboratory on nude men (28) had suggested that $0.14^{\circ}\text{C/kcal m}^2 \text{ hr}$ of resistance to heat loss was provided simply by the still air layer surrounding the body, (I_A), leaving $0.18^{\circ}\text{C/kcal m}^2 \text{ hr}$ as the defined 1 clo resistance of a standard business suit. For simplicity, the heat loss allowed through insulation of clothing is usually presented rather than the resistance; i.e. so 1 clo of insulation allows $1/0.18$ or $5.55 \text{ kcal/m}^2 \text{ hr}$ of heat loss per $^{\circ}\text{C}$ of difference between the skin and surrounding temperature.

This empirically derived original definition still serves as a common base for characterizing clothing. The intrinsic insulation (I_{clo}) value of today's typical items office clothing can be characterized as shown in Table 1, derived from studies at Kansas State University (26); suggested formulations for summing to obtain a "TOTAL" insulation for men's and women's clothing are included at the bottom of the table. Typical indoor clothing worn in offices today range from 0.4 clo in summer (short, light dress; light slacks and short sleeved shirt) to 0.6 clo in spring and fall (heavy, short sleeved top and skirt; long sleeved shirt and trousers) to perhaps 1.0 clo in winter (heavy slacks, light sweater and blouse and

jacket; heavy trousers, sweater and shirt and jacket). As a rule of thumb, it has been suggested (1) that the air temperature for comfort can be offset by 1°F for each 0.1 clo deviation from the usual 0.6 clo insulation baseline for individuals doing sedentary to light office work (100 to 200 kcal/hr), and by 2°F for each 0.1 clo deviation at higher work levels; i.e. if 1.0 clo of insulation were worn, the 78°F midpoint in the ASHRAE comfort chart for office workers wearing the usual 0.6 clo of insulation could be lowered to 74°F for light work and to 70°F for heavier work, just by this behavioral temperature regulation of clothing selection.

There are limits to how far such behavioral regulation can go (20,21), especially in the practical case of office work. As can be seen in Table II, where I have attempted to relate the classic ASHRAE comfort vote (where 4 is neutral, 1 is cold and 7 is hot) to a range of ET^* and associated comfort sensations, mean skin temperatures and % wettedness, the onset of cool thermal discomfort is initially a function of toe (and finger) temperatures. Adding more torso clothing (20,21) may help delay vasoconstriction, thus maintaining circulatory heat flow to the toes and fingers (and wearing a hat to prevent heat loss from the head, where vasoconstriction does not occur and thus a great proportion of the bodies heat production can be lost) is only a temporary expedient unless total heat balance can be maintained. As Sheard suggested in 1938 (25), the hands and feet act as error regulators for the body and the reduction of their circulatory heat input is dramatic. We agree with Van Dilla (27) that the $72 \text{ kcal/m}^2 \text{ hr}$ of circulatory heat input to the fingers of a comfortable resting subject falls, acutely, to $7 \text{ kcal/m}^2 \text{ hr}$ when the subject is chilled. Adding insulation directly to the feet, in the form of heavier socks and larger (i.e. thicker) footwear can provide some delay in cooling, but the key is maintenance of circulatory heat input at comfortable

levels by increased metabolic heat production (through increased work, since shivering is not associated with comfort) and by decreasing overall heat loss by adding clothing overall the body. Ultimately, since clothing insulation is a function of the thickness of the trapped air layer the bulkiness of the clothing becomes a practical limitation to foot and torso insulation; c@ (4 clo of insulation is provided on a flat surface by a 1 inch thickness of conventional clothing materials, whether of wool, cotton or synthetic fiber), so there is no foreseeable solution from improved clothing materials.


The hands, ultimately, are the limiting factor to dropping office temperatures to conserve energy, since: a) it is difficult to perform most work wearing gloves; b) the resistance of a glove to heat loss is a function of its thickness; c) for a thin cylinder such as a finger, the increase in surface area for heat loss parallels the increase in thickness, so that it has proven impossible to design a practical mitten ensemble which will provide more than about 1.2 clo intrinsic insulation around the fingertips. Thus the hands, and to a more treatable degree the feet, are the ultimate limitation to energy conservation by lowering the thermostat.

In his more recent studies, Pharo and his later collaborators at the Pierce Laboratories, especially Nishi and Gonzales, have developed methods for describing the evaporative heat transfer limitations imposed by conventional clothing. However, the problem of avoiding discomfort in the heat is, as shown in Table II, primarily a function of minimizing the percent of the body surface area that is sweat wetted; this is most easily accomplished by removing clothing and exposing bare skin. If one avoids special treatments, or impermeable items like plastic raincoats or the "wind shirts" used by skiers, the evaporative heat transfer coefficient (h_c) is directly relatable to the convective heat transfer coefficient (h_c)

by the Lewis Relationship:

$$h_e = 2.2 h_c$$

so there is little that can be done with clothing to reduce the percent sweat wetted area, other than to remove as much clothing and expose as much skin as possible. While raising the thermostat level for air conditioning as an energy conservation measure, social standards will therefore be the limiting feature to avoid an increase of the body's sweat wetted surface area to, and above, the 20% level considered as the threshold for discomfort in the heat. While it is accepted practice for men in Australia to wear shorts as office clothing, shorts for men and women are far from acceptable norms in even the hottest areas of the United States today; the blossoming of industry in the Southern U. S. has been a function of the air-conditioning industry as much as anything else.

To summarize "The Role of Clothing in Achieving Acceptability of Environmental Temperatures between 65° and 85°F," ^{It} seems clear that the trend, since the 1920's, to lighter weight and less clothing will have to be reversed completely in the winter if thermal comfort is to be achieved at the present ^{Federal Energy Agency} FEA guidelines of 68° to 70°F for winter thermostat settings, (105, 11) and because of the problem of the hands thermal comfort may not be achievable to allow for sedentary office work at temperatures below that level. The present summertime guidelines of 78 to 80°F can be achieved with conventional summer clothing, and even the proposed extended guidelines of 80 to 82°F could be made thermally comfortable if bathing suits become acceptable as office wear. 

I have had to omit a great many of Pharo's significant contributions to this area (T_o , T_{oh} , F_{cl} , F_{pcl} , etc.) to stay within my appointed topic. I would like to

salute Pharo on his second, or is it third retirement; not with the classic Latin "Ave atque Vale", Hail and Farewell, since I hope to see a good deal more of him over the next few years, but instead with an even older language - that which appears on Yale's seal:

"Key lecach tov nosarte lochem, torahse al taazovu. "

Behold, we have been given good doctrine, let us not forsake it.

Table I clo insulation units for individual items of clothing and formulae for obtaining total intrinsic insulation.

<u>Clothing</u>	<u>MEN</u>		<u>WOMEN</u>
Underwear			
Sleeveless	0.06		Bra and Panties 0.05
T shirt	0.09		Half Slip 0.13
Underpants	0.05		Full Slip 0.19
Torso			
Shirt			Blouse
Light, short sleeve	0.14		Light 0.20 ¹
long sleeve	0.22		Heavy 0.29 ¹
Heavy, short sleeve	0.25		Dress
long sleeve	0.29		Light 0.22 ^{1,2}
(Plus 5% for tie or turtleneck)			Heavy 0.70 ^{1,2}
Vest			Shirt
Light	0.15		Light 0.10 ²
Heavy	0.29		Heavy 0.22 ²
Trousers			Slacks
Light	0.26		Light 0.26
Heavy	0.32		Heavy 0.44
Sweater			Sweater
Light	0.20 ¹		Light 0.17 ¹
Heavy	0.37 ¹		Heavy 0.37 ¹
Jacket			Jacket
Light	0.22		Light 0.17
Heavy	0.49		Heavy 0.37
Footwear			
Socks			Stockings
Ankle Length	0.04		Any length 0.01
Knee High	0.10		Panty Hose 0.01
Shoes			Shoes
Sandals	0.02		Sandals 0.02
Oxfords	0.04		Pumps 0.04
Boots	0.08		Boots 0.08

$$\text{TOTAL I} = 0.727 \sum \text{individual items} + 0.113 \sum = 0.770 \text{ items} + 0.05$$

1. Less 10% if short sleeve or sleeveless
2. Plus 5% if below knee length, less 5% if above.

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Table II. Comfort vote, and the temperature sensation as a function of ET^* and the associated mean skin temperature and percent wettedness.

COMFORT VOTE	TEMPERATURE SENSATION	$ET^*_{(1)}$	COMFORT SENSATION	$\bar{T}_s^{(2)}$	$\%A_{sw}^{(3)}$
1	Very Cold	10°C	Uncomfortable	30°C	
1	Cold	15°C		30.5°C	
2	Cool	20°C	Slightly Uncomfortable	32°C	
3	Slightly Cool	25°C	Comfortable	32.5°C ($T_{\text{toes/fingers}}$)	
4	Neutral			34°C	6
5	Slightly Warm	30°C		35°C	
6	Warm	35°C	Slightly Uncomfortable	-	20
7	Hot	40°C	Very Uncomfortable	-	40 60 80
	Very Hot	45°C	Limited Tolerance	($T_{\text{core}} - \bar{T}_s$)	100

(1) Air temperature (T_{db}) at 50% RH with air movement $\approx 0.4 \text{ m/s}$ wearing standard long sleeved shirt or trousers (0.6 clo intrinsic).

(2) Mean Weighted Skin Temperature

(3) Percent of skin area sweat wetted $\approx \text{Skin relative humidity} \approx E_{\text{req}}/E_{\text{max}}$

The views of the author do not purport to reflect the positions of the Department of the Army or the Department of Defense.

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